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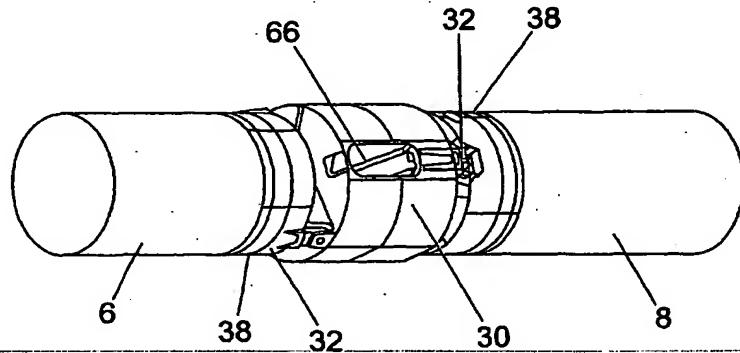
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(54) Title: WAVE POWER APPARATUS



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(57) Abstract: Wave power apparatus (2) comprising a plurality of Wave power apparatus (2) comprising a plurality of buoyant elongate body members(4, 6, 8, 10), at least one adjacent pair of body members (4, 6, 8, 10) being interconnected by a linkage unit (30) to form an articulated chain, each body member (4, 6, 8, 10) of said pair being connected to the respective linkage unit (30) by linkage means (31) permitting relative rotation of the body members (4, 6, 8, 10); and power extraction means (40) adapted to resist and extract power from the relative rotation The power extraction means (40) being located substantially within each linkage unit (30).

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1 Wave Power Apparatus

2

3 This invention relates to a linkage unit, apparatus
4 and method, for extracting power from water waves,
5 particularly ocean waves.

6

7 Ocean waves represent a significant energy resource.
8 It is known to use a wave energy converter to
9 extract power from such waves. An improved
10 apparatus is shown in our WO 00/17519. This shows
11 apparatus for extracting power from ocean waves
12 comprising a number of buoyant cylinder body members
13 connected together at their ends to form an
14 articulated chain-like structure. Each pair of
15 adjacent cylindrical members is directly connected
16 together by coupling members which permit relative
17 rotation of the cylindrical members about at least
18 one axis. Preferably, adjacent coupling members
19 permit relative rotation about mutually orthogonal
20 transverse axes.

21

1 It is an object of the present invention to provide
2 further improved apparatus and method for extracting
3 power from waves.

4

5 According to a first aspect of the present
6 invention, there is provided wave power apparatus
7 comprising:

8 a plurality of buoyant elongate body
9 members, at least one adjacent pair of body
10 members being interconnected by a linkage unit
11 to form an articulated chain, each body member
12 of said pair being connected to the respective
13 linkage unit by linkage means permitting
14 relative rotation of the body members; and

15

16 power extraction means adapted to resist
17 and extract power from the relative rotation,
18 the power extraction means being located
19 substantially within each linkage unit.

20

21 Preferably the body members are arranged
22 consecutively in an articulated apparatus, each
23 adjacent pair of body members being interconnected
24 by a linkage unit to form an articulated chain.

25

26 Preferably the or each linkage unit has a
27 longitudinal length substantially shorter than the
28 body members.

29

30 Preferably the body members substantially comprise
31 hollow members devoid of active components.

32

- 1 Preferably each body member has one or more end caps
- 2 with corresponding linkage means to marry with the
- 3 linkage means of the linkage unit.
- 4
- 5 Preferably the linkage unit is arranged to permit
- 6 relative rotation between the linkage unit and a
- 7 first body member about a first axis of rotation at
- 8 a first end of the linkage unit, and to permit
- 9 relative rotation between the linkage unit and a
- 10 second body member about a second axis of rotation
- 11 at a second end of the linkage unit.
- 12
- 13 Preferably the power extraction means includes a
- 14 hydraulic ram assembly.
- 15
- 16 Preferably the hydraulic ram assembly comprises a
- 17 plurality of rams.
- 18
- 19 Preferably the power extraction means includes a
- 20 hydraulic ram assembly for each axis of rotation.
- 21
- 22 Preferably the power extraction means includes two
- 23 hydraulic ram assemblies acting about each axis of
- 24 rotation.
- 25
- 26 Preferably the end caps have a number of cavities to
- 27 receive respective ends of the power extraction
- 28 means.
- 29
- 30 Preferably the power extraction means has at least
- 31 one seal, such as a bellows or diaphragm seal, to

1 prevent ingress of water into the linkage unit
2 and/or body members.

3

4 Preferably the linkage unit includes one or more
5 power generation or storage means connected to one
6 or more of the power extraction means.

7

8 Preferably the linkage unit includes a first power
9 generation means connected to one or more power
10 extraction means at one axis of rotation, and a
11 second power generation means connected to one or
12 more power extraction means at the other axis of
13 rotation.

14

15 Preferably the first or second power generation
16 means is connectable to at least one power
17 extraction means from each axis of rotation, such
18 that the restraint of the linkage unit is maintained
19 in the event of failure of one of the power
20 extraction or generation means.

21

22 Preferably the first and second power generation
23 means is connectable to one or more of the power
24 extraction means from one or both axes of rotation,
25 such that when the apparatus is operating at partial
26 capacity, the one or more power extraction means is
27 connected solely to the first or second power
28 generation means.

29

30 Preferably constraint is applied to each power
31 extraction means of the linkage unit in order to
32 induce a cross-coupled response which may be tuned

1 to be resonant in small waves to increase power
2 capture and which may be set in large waves to limit
3 power absorption and maximise survivability.

4

5 Preferably the apparatus includes one or more of a
6 ballasting system, mooring system, and means to
7 apply a roll bias angle to the axes of rotation.

8

9 Preferably the linkage unit includes access means,
10 such as one or more hatches, to allow inspection,
11 repair and maintenance on or off site.

12

13 The power extraction means may be integral with,
14 linked to or separate from the linkage means.

15

16 In one embodiment of the present invention, separate
17 linkage means are provided for the movement about
18 each axis. Each linkage means may be independent,
19 or may be linked to other linkage means.

20

21 The nature of the buoyant body members may
22 correspond with the description of said members in
23 WO 00/17519, which is included herein by way of
24 reference. That is, said body members are
25 preferably substantially elongate, cylindrical, and
26 will form a chain-like structure. The apparatus
27 preferably has a length of the same order of
28 magnitude as the longest wavelength of the waves
29 from which power is extracted, and may be free to
30 adopt an equilibrium position with respect to any
31 instantaneous wave pattern.

1 The linkage unit preferably includes one or more
2 controllers, more preferably one controller or
3 control means within the linkage unit. The linkage
4 unit preferably includes sufficient access means,
5 such as one or more hatches, to allow inspection,
6 repair and maintenance on site, i.e. as located
7 between two body members at sea.

8

9 The apparatus may be further defined and used as
10 described in WO 00/17519. This includes possibly
11 including a slack mooring system, and possibly
12 having means to orientate the apparatus such that
13 under normal operating conditions, it spans at least
14 two wave crests. The mooring system may also
15 include means to vary the angle of orientation of
16 the chaining of body members to the mean wave
17 direction to maximise power extraction. The
18 apparatus may also further comprise means to apply a
19 roll angle to an axis of relative rotation away from
20 the horizontal and/or vertical.

21

22 The apparatus may also include one or more elements
23 adapted to resist relative rotational movement of
24 said body members, which may be a spring and/or
25 damping elements. Magnitudes of constraint could be
26 applied to a plurality of said elements in order to
27 induce a cross-coupled response.

28

29 The apparatus could also be provided with a
30 ballasting system, which possibly comprises ballast
31 tanks comprising inlet means and outlet means, and

1 wherein the ballasting system varies the roll bias
2 angle of the chain-like structure.

3

4 According to a second aspect of the present
5 invention, there is provided a linkage unit for use
6 in the apparatus of claim 1, comprising:

7

8 linkage means for interconnection between
9 the body members permitting relative rotation
10 at either end of the unit;

11

12 power extraction means adapted to resist
13 and extract power from the relative rotation of
14 the body members;

15

16 the power extraction means being located
17 substantially within the linkage unit.

18

19 Preferably the linkage unit is arranged to permit
20 relative rotation between the linkage unit and a
21 first body member about a first axis of rotation at
22 a first end of the linkage unit, and to permit
23 relative rotation between the linkage unit and a
24 second body member about a second axis of rotation
25 at a second end of the linkage unit.

26

27 Preferably the power extraction means includes a
28 hydraulic ram assembly.

29

30 Preferably the hydraulic ram assembly comprises a
31 plurality of rams.

32

- 1 Preferably the power extraction means includes a
2 hydraulic ram assembly for each axis of rotation.
3
- 4 Preferably the power extraction means includes two
5 hydraulic ram assemblies acting about each axis of
6 rotation.
7
- 8 Preferably the power extraction means has at least
9 one seal, such as a bellows or diaphragm seal, to
10 prevent ingress of water into the linkage unit
11 and/or body members.
12
- 13 Preferably the linkage unit includes one or more
14 power generation or storage means connected to one
15 or more of the power extraction means.
16
- 17 Preferably the linkage unit includes a first power
18 generation means connected to one or more power
19 extraction means at one axis of rotation, and a
20 second power generation means connected to one or
21 more power extraction means at the other axis of
22 rotation.
23
- 24 Preferably the first or second power generation
25 means is connectable to at least one power
26 extraction means from each axis of rotation, such
27 that the restraint of the linkage unit is maintained
28 in the event of failure of one of the power
29 extraction or generation means.
30
- 31 Preferably the first and second power generation
32 means is connectable to one or more of the power

1 extraction means from one or both axes of rotation,
2 such that when the apparatus is operating at partial
3 capacity, the one or more power extraction means is
4 connected solely to the first or second power
5 generation means.

6

7 Preferably constraint is applied to each power
8 extraction means of the linkage unit in order to
9 induce a cross-coupled response which may be tuned
10 to be resonant in small waves to increase power
11 capture and which may be set in large waves to limit
12 power absorption and maximise survivability.

13

14 Preferably the linkage unit includes access means,
15 such as one or more hatches, to allow inspection,
16 repair and maintenance on site.

17

18 According to a third aspect of the present
19 invention, there is provided a method of extracting
20 power from waves comprising the steps of:

21

22 deploying an apparatus as described in the
23 first aspect of the present invention;

24

25 orientating the structure such that a front end
26 of the structure faces into the oncoming waves;
27 and

28

29 extracting the power absorbed in the or each
30 linkage unit.

31

1 Preferably the apparatus of the method includes
2 independent systems for each axis of relative
3 movement, and means to operate each system either
4 independently or in a linked action. One advantage
5 of this is that the failure of one system still
6 allows the other system to operate independently,
7 maintaining restraint on the linkage. Alternatively
8 or additionally, where there are a plurality of
9 individual linkage means or power extraction means
10 acting about each axis of rotation, the apparatus
11 may include further independent systems that are
12 split or otherwise designed in such a way that in
13 the event of failure on one of the systems,
14 restraint may be maintained about both or all axes
15 of relative movement.

16
17 According to a fourth aspect of the present
18 invention, there is provided a method of manufacture
19 of apparatus according to the first aspect of the
20 present invention, comprising the step of:

21
22 interconnecting each pair of adjacent body
23 members of the apparatus with a linkage unit
24 described in the second aspect of the present
25 invention.

26
27 Preferably the body members and linkage unit(s) are
28 connected together close to or on site.

29
30 Preferably the linkage unit(s) are fully assembled
31 and tested before being transported to site.

32

1 Preferably the method can be carried out close to
2 site, on site or in situ, because the linkage
3 unit(s) can be fully assembled, analysed and tested,
4 for example on a test rig, relating to its power
5 extraction prior to its installation and use.

6

7 Embodiments of the present invention will now be
8 described by way of example only with reference to
9 the accompanying drawings in which:

10

11 Figures 1a and 1b show overall plan and side views
12 of apparatus of the present invention;

13

14 Figure 2 shows a perspective view of part of prior
15 art apparatus according to the one embodiment of the
16 invention shown in WO 00/17519 for directly linking
17 body members;

18

19 Figure 3 shows front and inside detail of one part
20 of Figure 2;

21

22 Figure 4 shows a schematic line drawing of the
23 conjunction in Figures 2 and 3;

24

25 Figure 5 shows a detail of the apparatus in Figure 1
26 illustrating a linkage unit of the present
27 invention;

28

29 Figures 6, 7 and 12 show different external and
30 part-internal views of the linkage unit in Figure 5;

31

1 Figure 8a shows detail of the linkage between the
2 linkage unit and a buoyant body member;

3

4 Figure 8b shows detail in circle A in Figure 8a;

5

6 Figure 8c shows detail of the dual seal system in
7 circle B in Figure 8a;

8

9 Figure 9 shows a front perspective internal detail
10 of a linkage unit of Figure 5;

11

12 Figure 10 shows a front plan internal line drawing
13 of linkage unit of Figure 9; and

14

15 Figures 11a and 11b show two schematic hydraulic
16 systems for the linkage unit.

17

18 Referring to the drawing, Figures 1a and 1b show an
19 apparatus 2 for extracting power from waves having,
20 for this example, four buoyant body members 4, 6, 8,
21 10. The number, size and shape of the body members
22 involved is generally determined by the annual wave
23 climate of the locality in which it is used, and by
24 the conditions it is likely to encounter.

25

26 The body members 4, 6, 8, 10 may be of any size or
27 shape. They are substantially hollow and may be
28 cylindrical or non-cylindrical. If cylindrical,
29 they may be of circular or non-circular cross-
30 section. Generally the body members 4, 6, 8, 10 are
31 cylindrical, and have sufficiently small depth and
32 freeboard to experience complete submergence and

1 emergence in large waves (as is discussed in our WO
2 00/17519). That is, the overall chain-like
3 structure of the apparatus 2 may be configured to
4 encourage hydrostatic clipping in extreme
5 conditions. The body members 4, 6, 8 and 10 may be
6 provided with fins, bilge keels or other protrusions
7 to add hydrodynamic damping to any direction of
8 motion desired.

9

10 The front body member 4 is provided with a
11 streamlined (for example conical) front end to
12 minimise drag in extreme seas, whilst the rear body
13 member 10 has a flat rear end to increase damping
14 along the axis of the chain structure to add damping
15 to the mooring response.

16

17 The body members 4, 6, 8, 10 may be formed from any
18 suitable material. Concrete is one suitable
19 material, although steel or fibreglass are also
20 useable.

21

22 The body members 4, 6, 8, 10 are preferably
23 ballasted to float with its centre line on or near
24 the water-plane (approximately 50% displacement by
25 volume). The body members 4, 6, 8, 10 could include
26 an active or passive ballasting system, which varies
27 the level at which the individual body members or
28 the complete apparatus floats. If incorporated, the
29 ballasted system may be capable of being disabled
30 and/or removed. The ballasting system hastens the
31 onset of hydrostatic clipping in extreme seas, thus
32 helping to minimise the maximum loads and bending

1 moments which the apparatus 2 is subject to in
2 adverse weather conditions. A variable ballasting
3 system useable with the present invention is shown
4 and discussed in our WO 00/17519.

5

6 Figures 2-4 show one arrangement for connecting two
7 similar body members of the apparatus for extracting
8 power shown in WO 00/17519. Between the body
9 members 12 of the prior art apparatus 11, there is
10 shown a joint spider 14 adapted to provide
11 rotational movement directly between the body
12 members 12 about two orthogonal axes. Seals 16
13 cover stubs 17, shown more clearly in Figure 4,
14 which actuate rams 18 in sealed compartments 20 at
15 the end of each body member 12.

16

17 Whilst the known arrangement shown in Figures 2-4
18 provides the benefit of a wave energy apparatus or
19 converter, it requires the manufacture and use of
20 the linkage mechanisms and power extraction means or
21 ram-housing compartments to be made and attached
22 separately to the remaining parts of the body
23 members 12. A typical length of a body member is 27
24 meters long, requiring either significant
25 transportation of completed body members made in a
26 suitable location, or significant assembly of the
27 separate compartments 20 to the main lengths of body
28 members 12 on site, generally at or near beaches and
29 other sea locations, which may not provide suitable
30 assembly conditions.

1 Furthermore, each ram-housing compartment 20
2 requires its own power generation means or
3 components and connected hydraulic systems, and must
4 be separately tested prior to installation and use.
5 Such testing may or may not be in conjunction with
6 the main part of the body members 12, being 27
7 meters long. Also, in the event of failure of the
8 linkage or joint hydraulic system, restraint on the
9 joint may be lost, possibly leading to further
10 damage or failure. Whilst it is possible to provide
11 independent systems in this arrangement for each of
12 the individual restraint means acting about a
13 particular axis of rotation, it is not economic to
14 do so.

15

16 As shown in Figures 1, 5, 6 et al, the present
17 invention provides a linkage unit 30 for
18 interconnection between a plurality of adjacent
19 buoyant body members 4, 6, 8, 10. Each adjacent
20 pair of body members 4, 6, 8, 10 is interconnected
21 by a linkage unit to form an articulated chain,
22 consecutively arranged. The linkage unit 30
23 comprises linkage means 31 to conjoin the unit 30
24 with the respective ends of each adjacent pair of
25 body members 4, 6, 8, 10 to permit relative movement
26 of said body members 4, 6, 8, 10 about two axes of
27 rotation.

28

29 The linkage unit 30 may be of any shape and size
30 determined by the annual wave climate of the
31 locality in which it is used, and by the weather
32 conditions it is likely to encounter, i.e. the shape

1 and size will be site-specific. Generally, the
2 linkage unit 30 is the same shape as the body
3 members 4, 6, 8, 10, for example cylindrical, and
4 has a longitudinal length substantially shorter than
5 the body members, for example approximately 5
6 meters, but may be of similar length to the body
7 members.

8

9 The linkage means 31 is shown in more detail in
10 Figures 7 and 8a. Each end of the linkage unit 30
11 has a set of two bearings 32, each set of bearings
12 32 set at substantially orthogonal angle to the
13 other set. Each set of bearings 32 is adapted to
14 hold a pin 34 (not shown in Figure 7) along each
15 axis.

16

17 Also attachable to each pin 34 are bearings 36 on
18 the relevant ends of the adjacent pair of body
19 members 4, 6, 8 and 10. The body member bearings 36
20 are preferably conjoined with the main segments of
21 the body members 4, 6, 8, 10 by means of end-member
22 caps 38, made for example of steel. Thus, an end
23 cap 38 need only comprise a cast or otherwise
24 manufactured piece having two bearings and two ram
25 housings or cavities 35. No moving parts are
26 involved, leading to significantly reduced
27 manufacture, attachment, maintenance and repair,
28 etc. Moreover, there are no complex or active
29 components, for example, power extraction means,
30 hydraulic systems, power generation or storage
31 means, accumulators, motors, low pressure
32 reservoirs, heat exchangers, gas backup bottles

1 etc., within the body members 4, 6, 8, 10. The
2 linkage bearings 32, 36 may be provided with
3 external seals 41 to allow the bearings and pins 34
4 to be accessed for inspection, maintenance or repair
5 insitu or near-site without water ingress into the
6 linkage unit and/or body members.

7

8 Thus, each linkage unit 30 allows rotational
9 movement about one axis with one body member 4, 6,
10 8, 10, and rotational movement about an orthogonal
11 axis with its other conjoined body member 4, 6, 8,
12 10. In this way, the linkage unit 30 allows the
13 body members 4, 6, 8, 10 relative movement about two
14 axes (based along the axes of the pins 34).

15

16 The relative movements between the linkage units 30
17 and body members 4, 6, 8 and 10 are resisted and
18 extracted by power extraction means which extract
19 power from this relative motion. The power
20 extraction means may be any suitable means adapted
21 to be activated by this relative motion. One such
22 means is a damping element in the form of a
23 hydraulic ram and piston assembly.

24

25 In the present embodiment of the invention shown,
26 two hydraulic ram assemblies 40 are provided at each
27 end of the linkage unit 30, and on each side of the
28 linkage unit-body member linkage means. The parts
29 of the assemblies 40 between the unit 30 and end
30 caps 38 will generally be enclosed by flexible seals
31 41 to accommodate axial motion of the ram assemblies
32 40 extending and retracting, as known in the art.

1 Inner diaphragm seals 43 could also be incorporated
2 to assist single seal-failure problems, as shown in
3 Figure 8c. The inner diaphragm seals 43 accommodate
4 small slewing motion of respective ends of the ram
5 assemblies 40.

6

7 As shown in Figure 8b, the end of the ram of a ram
8 and piston assembly 40 can travel along a suitable
9 ram cavity 35 within the end cap 38 of a body member
10 4, 6, 8, 10. The role of the cavity 35 is two-fold:

11

- 12 1. To provide a sealed compartment to prevent
13 water ingress into the end caps 38 in the event
14 of failure of the external flexible seal 41,
15 and,
- 16 2. In the event of failure of the hydraulic
17 systems, to allow the ram 40 to break free at
18 the attachment pin 45 if it reaches its end
19 stop (in a manner similar to a shear pin on
20 outboard motor propellers). This limits the
21 maximum loads that the structure must be
22 designed to sustain, reducing cost and the
23 likelihood of major or complete failure. In
24 the event of the shear pin breaking, the cavity
25 35 is provided with a weak end wall to allow
26 the ram 40 to punch through, and therefore give
27 greatly increased joint motion to prevent
28 extreme loads in the structure.

29

30 Figure 8b does not show the inner and outer seals 41
31 and 43 for clarity.

32

1 Figures 9 and 10 show internal details of the
2 linkage unit 30. One set of bearings 32 are shown,
3 set at a substantially orthogonal angle to two
4 hydraulic ram assemblies for connecting the shown
5 face of the linkage unit 30 to a body member 4, 6,
6 8, 10.

7

8 Ram assemblies 42A, 42B are substantially sway rams,
9 as shown in Figure 10. However they are not solely
10 sway rams as the rams 42A, 42B can be used to induce
11 a cross-coupled response which may be tuned to be
12 resonant in small waves to increase power capture
13 and which may be set in large waves to limit power
14 absorption and maximise survivability.

15

16 One end of these rams 42A, 42B are rotatably
17 attached to a pin 45 within a cavity 35 located in
18 the cap-end 38 of an adjacent body member 4, 6, 8,
19 10.

20

21 Figure 10 shows orthogonally located hydraulic ram
22 assemblies 44A, 44B which are substantially, but not
23 solely, heave rams which can also be used to induce
24 a cross-coupled response as described in the above
25 paragraph.

26

27 These heave rams 44A, 44B are attached to a pin 45
28 within a cavity 35 located in the cap end 38 of an
29 opposing adjacent body member 4, 6, 8, 10.

30

31 Heave ram 44A and sway ram 42A are connected to a
32 first main manifold 46 which can feed towards a

1 central manifold 48. Similarly, Heave ram 44B and
2 sway ram 42B are connected to a second main manifold
3 50 which can feed via a one way valve into the
4 central manifold 48. The central manifold 48
5 controls top and bottom motors 52, 54.

6

7 Figures 9 and 10 also show accumulators 84 and 86
8 and reservoirs 88 and 90 which feed into the central
9 manifold 48, as well as gas backup bottles 80 and
10 82. The back-up bottles 80 and 82 provide the
11 optimum gas to oil volume ratio ensuring optimal
12 energy storage over the required pressure range.

13

14 In use, the rams 42, 44 pump high pressure oil into
15 the accumulators 84, 86 via the manifolds 46, 48 and
16 50. The pressure in the accumulators 84, 86 can be
17 matched to the incident sea state by controlling the
18 rate at which the oil flows out through the motors
19 52, 54.

20

21 The configuration shown in Figures 9 and 10 has the
22 advantage of being two sets of hydraulic and
23 generation components providing split hydraulic
24 circuits through the two main manifolds 46, 50.
25 This gives the system redundancy in the event of
26 failure of a single circuit, allowing the system to
27 maintain restraint of the joint between the body
28 members 4, 6, 8, 10. This concept is similar to
29 that of dual circuit brakes on a car. This is shown
30 in more detail in Figures 11a and 11b.

1 Figure 11a shows schematically a first useable split
2 hydraulic circuit system inside the linkage unit 30.
3 The first circuit system is effectively split by
4 axis of rotation, such that sway rams 42A and 42B
5 serve a first circuit by feeding into one high
6 pressure accumulator 84, and heave rams 44A and 44B
7 serve a second circuit feeding into a second high
8 pressure accumulator 86, all through the outlet
9 valves 70. The pressured oil operates respective
10 hydraulic motors 52, 54, which can operate
11 respective electrical generators 60, excess pressure
12 going through respective heat exchanges 62 to low
13 pressure reservoirs 88 and 90, before returning to
14 the rams 42, 44 through inlet valves 72.
15
16 The two circuits meet at the common central manifold
17 48, such that for normal operation, the two circuits
18 can run linked, thereby increasing efficiency,
19 especially in small seas. Each half of the
20 hydraulic circuit can feed the separate hydraulic
21 motors 52, 54, set to allow generation when the
22 system is to be linked or to be separated.
23
24 With the circuits linked in small seas (when the
25 system is below 50% power), this allows a single
26 generator to be fed by both hydraulic circuits.
27 This minimises the working hours of each generator,
28 and allows the single generator to run at a nearer
29 full load, dramatically increasing efficiency. In
30 the event of a fault or leak with one half of the
31 system, the circuits can be separated to allow the
32 other half to function independently, maintaining

1 restraint on the joints. The control of the split
2 systems can be via bi-directional linking valves 58
3 in the central manifold 48.

4

5 Figure 11b shows schematically a second useable
6 split hydraulic circuit system, wherein the two
7 circuits are divided to separately serve the sway
8 rams 42 and heave rams 44 on each axis of rotation,
9 divided such that each system serves one ram from
10 each axis of rotation, ensuring that restraint is
11 maintained on both joint axes in the event of a
12 single hydraulic circuit system failing. Again, the
13 high-pressure accumulators 84 and 86 are linked by
14 bi-directional link valves 58 to allow separate or
15 linked operation of the circuits, depending upon sea
16 conditions.

17

18 The motors 52, 54 are connected to a power
19 conversion unit or units 60, which may comprise one
20 or more parts. The power from the unit 60 could be
21 connected directly to the grid, or used directly or
22 indirectly to produce a useful by-product. Examples
23 of useful by-products are hydrogen through
24 electrolysis, and desalinated water.

25

26 The linkage unit 30 also includes one or more heat
27 exchangers 62, such as an oil/water water heat
28 exchanger, to release excess absorbed power back
29 into the sea. This allows the linkage unit 30 to
30 continue generating at full capacity in extreme
31 conditions. In the event of electrical grid

1 failure, this also provides the necessary thermal
2 load.

3
4 The hydraulic oil used by the apparatus is
5 preferably specified to be biodegradable, and non-
6 toxic to water organisms.

7
8 The linkage unit 30 includes one or more access
9 portals such as hatches. In the embodiment shown in
10 the accompanying drawings, the linkage unit 30 has a
11 first man-assessable hatchway 64 and a larger main-
12 assessable hatchway 66. The linkage unit 30 may
13 also include a separate or equipment loading
14 hatchway.

15
16 Figure 12 shows a further schematic part cross-
17 sectional perspective of the linkage unit 30
18 attached to a buoyant body member 6. Parts of the
19 linkage unit 30 have not been shown in order to
20 better illustrate the position of parts of the power
21 conversion units already installed 92, and a further
22 part 94 being installed through the main-access
23 hatchway 66.

24 By housing all the significant components and parts
25 for the power extracting in one linkage unit, this
26 allows the unit to share components such as
27 manifolds, pipework, fittings, mountings, power
28 supply and batteries, etc. within a single unit,
29 compared with previous known wave energy converters,
30 including that shown in WO 00/17519. The unit 30 is
31 therefore adapted for maintenance or repair within

1 one unit, rather than requiring separate
2 inspections.

3

4 Furthermore, the collations of the components in a
5 single unit also allows their control to be carried
6 out by a single joint controller, leading to further
7 cost savings.

8

9 The configuration of the linkage unit 30 shown in
10 the attached drawings also allows the hydraulic oil
11 heat-exchangers 62 to be housed in the "U" channels
12 at the ends of the linkage unit 30. The use of a
13 'box-cooler' unit in this space means that it is
14 well protected, whilst generating sufficient flow of
15 water past it to keep the cooler compact.

16

17 A further improvement in the present invention is
18 the siting of the main bearings (and ram end
19 bearings) so as to allow access from inside the unit
20 30 (or the body member end caps 38) for inspection
21 and replacement. Preferably the unit 30 has
22 external seals around each component extending from
23 the unit 30, to prevent flooding, and to protect the
24 hydraulic rams and other components from corrosion.
25 This further assists when the inspection and/or
26 replacement of components is taken place, such that
27 the unit 30 does not have to be dry-docked for
28 maintenance or repair of a ram, seal or other
29 components. More preferably, each ram exit has two
30 flexible seals, e.g. as "inner" and "outer", to
31 provide back-up in the event of a failure.

32

1 A further advantage concerns the avoidance of the
2 use of a joint spider 14 as shown in Figures 2-4.
3 In this arrangement, the rams form the main load
4 path through the whole apparatus. This is because
5 the loads pass from one body member, through the
6 main bearing into the rear of the hydraulic ram, and
7 then pass straight through the module into the rod
8 end mount in the end of the next body member. In
9 the present invention, loads through the linkage
10 unit 30 are reduced to shear loads, other
11 environmental loads, and any small imbalance loads
12 due to the differential areas of the rams. This
13 means that the configuration can be more
14 structurally efficient. Moreover, as loads on the
15 linkage unit structure are small, access portal size
16 can be significantly larger making installation of
17 the components much easier. Lower structural loads
18 around access portals also allows simpler sealing
19 systems to be used.

20

21 The apparatus 2 is referenced predominantly against
22 itself rather than against the shore or the seabed.
23 This self referencing is achieved by the apparatus 2
24 being of length comparable to the incident
25 wavelength, and the apparatus 2 being orientated
26 relative to incident waves in a direction such that
27 the apparatus 2 spans at least two crests of the
28 incident waves.

29

30 The configuration and orientation of individual
31 joints, and the type and rating of individual power
32 extraction means which comprise a particular

1 apparatus, are selected to maximise the power
2 extracted from a given sea state, but to ensure
3 survival in extreme conditions. In particular an
4 overall roll bias angle (ψ) is preferably applied to
5 the joint axes away from the horizontal and vertical
6 so as to generate a cross coupling of the heave and
7 sway motions of the apparatus 2 in response to wave
8 forces. This response may be resonant with the
9 incoming waves to further increase power capture.
10 The roll bias angle is described in WO 00/17519.

11

12 Additionally or alternatively, the apparatus could
13 include an active system to control the roll bias
14 angle (ψ). In this way the active control system
15 also controls the response of the apparatus in
16 waves.

17

18 The same selection criteria determine the preferred
19 orientation in relation to incident waves of the
20 complete apparatus, when deployed.

21

22 Maximum power absorption by, and thus maximum power
23 output from, the apparatus is generally achieved by
24 coupling its body members using joints orientated in
25 different directions, by applying the roll bias
26 angle (ψ) to the joints, by applying different
27 constraints to each direction to induce a cross-
28 coupled response of varying magnitude and form which
29 may be tuned to suit the wave conditions, and by
30 using a system of moorings to present the apparatus
31 in a preferred orientation relative to incoming
32 waves.

1 The mooring system may also provide significant
2 physical restraint or excitation to the apparatus so
3 as to modify the overall response.

4

5 In calm weather, where wavelengths are relatively
6 short, and wave amplitudes are small, there is a
7 requirement to maximise power absorption by the
8 apparatus.

9

10 In extreme weather, where wavelengths are longer and
11 wave amplitudes are larger, survival of the
12 apparatus is of greater importance than power
13 absorption efficiency.

14

15 The total length of the assembled apparatus is
16 therefore selected to be sufficiently long to
17 provide adequate self referencing of itself in short
18 wavelengths where not much power is available and
19 there is a requirement to maximise power absorption,
20 and sufficiently short to 'hide' in long wavelengths
21 associated with storm waves in order to survive. If
22 the wavelength is much greater than the length of
23 the apparatus 2, then it cannot extend from peak to
24 peak, and the maximum movement of any part of the
25 apparatus 2 relative to any other part is less than
26 the amplitude of the wave, so that it 'hides' in the
27 long wavelength. In other words, the apparatus 2
28 loses the ability to reference itself against the
29 wavelength. This effect is further discussed in WO
30 00/17519.

1 Each end face of the intermediate body members 6, 8
2 and the linkage unit 30, and the inner end faces of
3 the end body members 4, 10, could be chamfered to
4 allow clearance for extreme joint motion. The
5 chamfered portions may lie on planes intersecting
6 the joint axes in order that opposing faces meet to
7 form a cushioning squeeze film. In the event that
8 end-stops of the ram assemblies are reached this has
9 the effect of reducing impact load.

10

11 The body members could also incorporate areas of
12 sacrificial structure which allow very large joint
13 angles before the overall structural integrity or
14 flotation of the apparatus is compromised. These
15 areas of sacrificial structure behave in a manner
16 similar to crumple zone on a car.

17

18 Other components of the apparatus and the ram
19 assemblies could similarly be designed to fail in a
20 benign manner which does not compromise the
21 integrity of the complete system when necessary.

22

23 In small seas, power capture can be maximised by
24 orientating the apparatus 2 at an angle to the
25 incident waves. In extreme seas, it is preferable
26 that the apparatus 2 be orientated end on to the
27 incident waves. This may be achieved by using an
28 active or passive mooring system to present the
29 apparatus 2 at an angle to the waves appropriate for
30 maximum power capture, or appropriate for survival,
31 as required. Illustrations of some possible mooring
32 configurations are shown in WO 00/17519.

1 The present invention provides a single, compact,
2 self-contained and manufacturable unit. This lends
3 itself to efficient, centralised manufacture and
4 testing, for shipment to a final assembly site.
5 Thus, the main body members could be manufactured
6 near the deployment site, and would require minimal
7 fit-out before final assembly with the linkage unit.
8 Further, the linkage units can be fully tested prior
9 to transportation and installation on-site.
10 Moreover, all the high technology, high valve and
11 data components are within a single unit.

1 Claims

2

3 1. Wave power apparatus comprising:

4

5 a plurality of buoyant elongate body
6 members, at least one adjacent pair of body
7 members being interconnected by a linkage unit
8 to form an articulated chain, each body member
9 of said pair being connected to the respective
10 linkage unit by linkage means permitting
11 relative rotation of the body members; and

12

13 power extraction means adapted to resist
14 and extract power from the relative rotation,
15 the power extraction means being located
16 substantially within each linkage unit.

17

18 2. Apparatus as claimed in claim 1, wherein the body
19 members are arranged consecutively in an articulated
20 apparatus, each adjacent pair of body members being
21 interconnected by a linkage unit to form an
22 articulated chain.

23

24 3. Apparatus as claimed in claim 1 or 2, wherein the
25 or each linkage unit has a longitudinal length
26 substantially shorter than the body members.

27

28 4. Apparatus as claimed in any preceding claim, in
29 which the body members substantially comprise hollow
30 members devoid of active components.

31

1 5. Apparatus as claimed in any preceding claim,
2 wherein each body member has one or more end caps
3 with corresponding linkage means to marry with the
4 linkage means of the linkage unit.

5

6 6. Apparatus as claimed in any preceding claim,
7 wherein the linkage unit is arranged to permit
8 relative rotation between the linkage unit and a
9 first body member about a first axis of rotation at
10 a first end of the linkage unit, and to permit
11 relative rotation between the linkage unit and a
12 second body member about a second axis of rotation
13 at a second end of the linkage unit.

14

15 7. Apparatus as claimed in any preceding claim,
16 wherein the power extraction means includes a
17 hydraulic ram assembly.

18

19 8. Apparatus as claimed in claim 7, wherein the
20 hydraulic ram assembly comprises a plurality of
21 rams.

22

23 9. Apparatus as claimed in claim 7 or 8, wherein the
24 power extraction means includes a hydraulic ram
25 assembly for each axis of rotation.

26

27 10. Apparatus as claimed in claim 9, wherein the
28 power extraction means includes two hydraulic ram
29 assemblies acting about each axis of rotation.

30

1 11. Apparatus as claimed in claim 5, wherein the end
2 caps have a number of cavities to receive respective
3 ends of the power extraction means.

4

5 12. Apparatus as claimed in any preceding claim,
6 wherein the power extraction means has at least one
7 seal to prevent ingress of water into the linkage
8 unit and/or body members.

9

10 13. Apparatus as claimed in any preceding claim,
11 wherein the linkage unit includes one or more power
12 generation or storage means connected to one or more
13 of the power extraction means.

14

15 14. Apparatus as claimed in claim 13, wherein the
16 linkage unit includes a first power generation means
17 connected to one or more power extraction means at
18 one axis of rotation, and a second power generation
19 means connected to one or more power extraction
20 means at the other axis of rotation.

21

22 15. Apparatus as claimed in claim 14, wherein the
23 first or second power generation means is
24 connectable to at least one power extraction means
25 from each axis of rotation, such that the restraint
26 of the linkage unit is maintained in the event of
27 failure of one of the power extraction or generation
28 means.

29

30 16. Apparatus as claimed in claim 14, wherein the
31 first and second power generation means is
32 connectable to one or more of the power extraction

1 means from one or both axes of rotation, such that
2 when the apparatus is operating at partial capacity,
3 the one or more power extraction means is connected
4 solely to the first or second power generation
5 means.

6

7 17. Apparatus as claimed in any preceding claim,
8 wherein constraint is applied to each power
9 extraction means of the linkage unit in order to
10 induce a cross-coupled response which may be tuned
11 to be resonant in small waves to increase power
12 capture and which may be set in large waves to limit
13 power absorption and maximise survivability.

14

15 18. Apparatus as claimed in any preceding claim,
16 wherein the apparatus includes one or more of a
17 ballasting system, mooring system, and means to
18 apply a roll bias angle to the axes of rotation.

19

20 19. Apparatus as claimed in any preceding claim,
21 wherein the linkage unit includes access means, such
22 as one or more hatches, to allow inspection, repair
23 and maintenance on or off site.

24

25 20. A linkage unit for use in the apparatus of claim
26 1, comprising:

27

28 linkage means for interconnection between
29 the body members permitting relative rotation
30 at either end of the unit;

31

1 power extraction means adapted to resist
2 and extract power from the relative rotation of
3 the body members;

4

5 the power extraction means being located
6 substantially within the linkage unit.

7

8 21. A linkage unit as claimed in claim 20, wherein
9 the linkage unit is arranged to permit relative
10 rotation between the linkage unit and a first body
11 member about a first axis of rotation at a first end
12 of the linkage unit, and to permit relative rotation
13 between the linkage unit and a second body member
14 about a second axis of rotation at a second end of
15 the linkage unit.

16

17 22. A linkage unit as claimed in claim 20 or 21,
18 wherein the power extraction means includes a
19 hydraulic ram assembly.

20

21 23. Apparatus as claimed in claim 22, wherein the
22 hydraulic ram assembly comprises a plurality of
23 rams.

24

25 24. A linkage unit as claimed in claim 23, wherein
26 the power extraction means includes a hydraulic ram
27 assembly for each axis of rotation.

28

29 25. A linkage unit as claimed in claim 24, wherein
30 the power extraction means includes two hydraulic
31 ram assemblies acting about each axis of rotation.

1 26. A linkage unit as claimed in any of claims 20 to
2 25, wherein the power extraction means has at least
3 one seal to prevent ingress of water into the
4 linkage unit and/or body members.

5

6 27. A linkage unit as claimed in any of claims 20 to
7 26, wherein the linkage unit includes one or more
8 power generation or storage means connected to one
9 or more of the power extraction means.

10

11 28. A linkage unit as claimed in claim 27, wherein
12 the linkage unit includes a first power generation
13 means connected to one or more power extraction
14 means at one axis of rotation, and a second power
15 generation means connected to one or more power
16 extraction means at the other axis of rotation.

17

18 29. A linkage unit as claimed in claim 28, wherein
19 the first or second power generation means is
20 connectable to at least one power extraction means
21 from each axis of rotation, such that the restraint
22 of the linkage unit is maintained in the event of
23 failure of one of the power extraction or generation
24 means.

25

26 30. A linkage unit as claimed in claim 29, wherein
27 the first and second power generation means is
28 connectable to one or more of the power extraction
29 means from one or both axes of rotation, such that
30 when the apparatus is operating at partial capacity,
31 the one or more power extraction means is connected

1 solely to the first or second power generation
2 means.

3

4 31. A linkage unit as claimed in any of claims 20 to
5 30, wherein constraint is applied to each power
6 extraction means of the linkage unit in order to
7 induce a cross-coupled response which may be tuned
8 to be resonant in small waves to increase power
9 capture and which may be set in large waves to limit
10 power absorption and maximise survivability.

11

12 32. A linkage unit as claimed in any of claims 20 to
13 31, including access means, such as one or more
14 hatches, to allow inspection, repair and maintenance
15 on site.

16

17 33. A method of extracting power from waves
18 comprising the steps of:

19

20 deploying an apparatus as claimed in any
21 of claims 1 to 19;

22

23 orientating the structure such that a front end
24 of the structure faces into the oncoming waves;
25 and

26

27 extracting the power absorbed in the or each
28 linkage unit.

29

30 34. A method of manufacture of apparatus according
31 to claims 1 to 19, comprising the step of:

32

1 interconnecting each pair of adjacent body
2 members of the apparatus with a linkage unit
3 according to claims 20 to 32.

4

5 35. The method of claim 34, wherein the body members
6 and linkage unit(s) are connected together close to
7 or on site.

8

9 36. The method of claim 34, wherein the linkage
10 unit(s) are fully assembled and tested before being
11 transported to site.

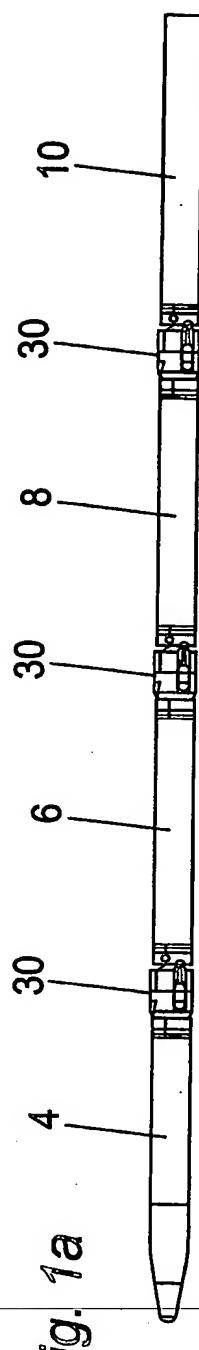


Fig. 1a

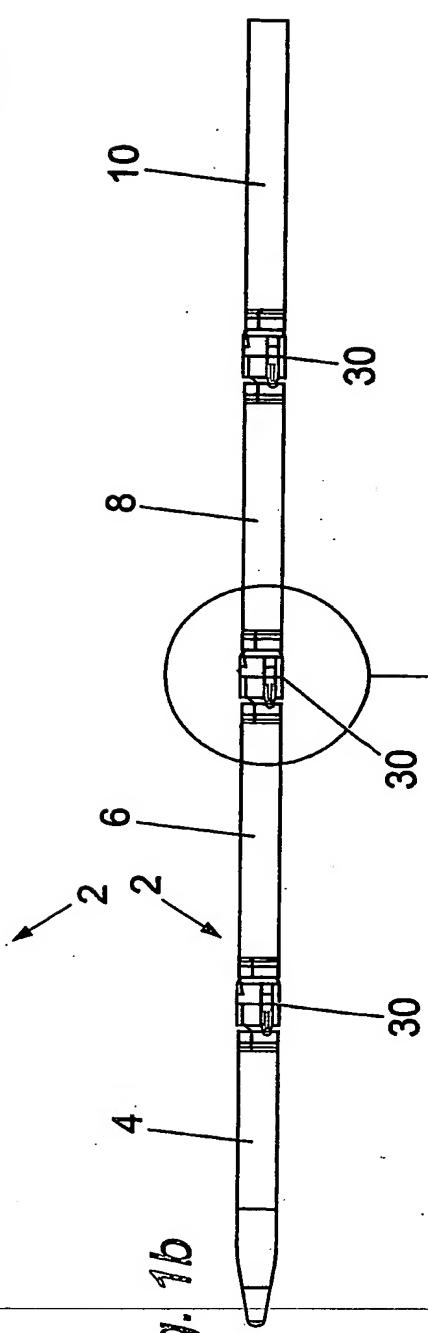


Fig. 1b

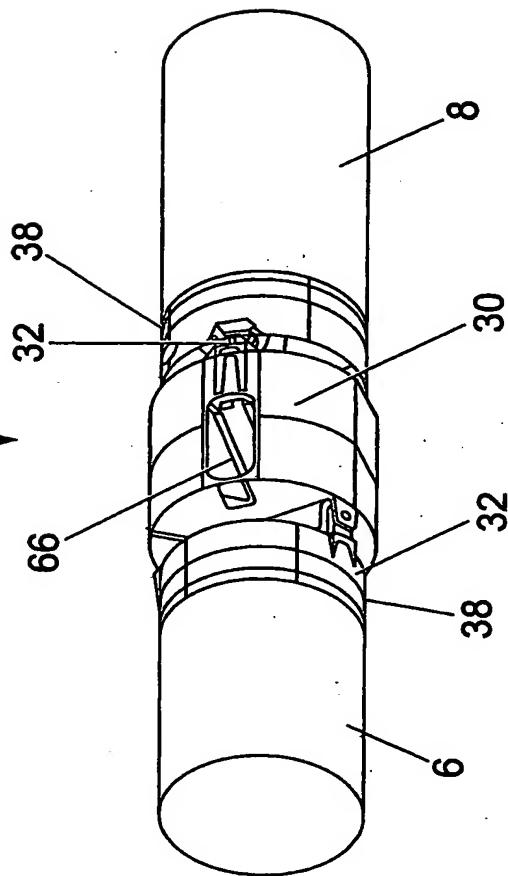
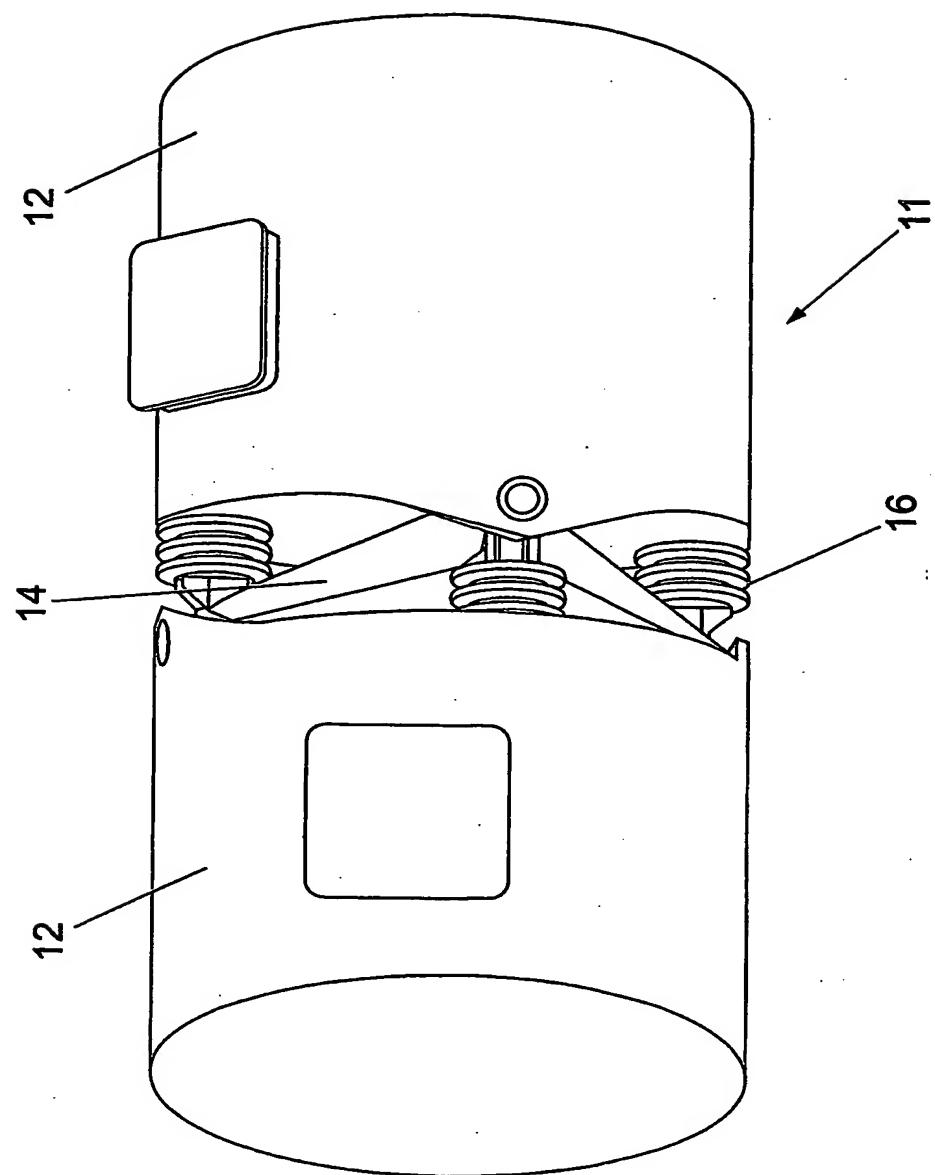


Fig. 5

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Fig. 2 Prior Art



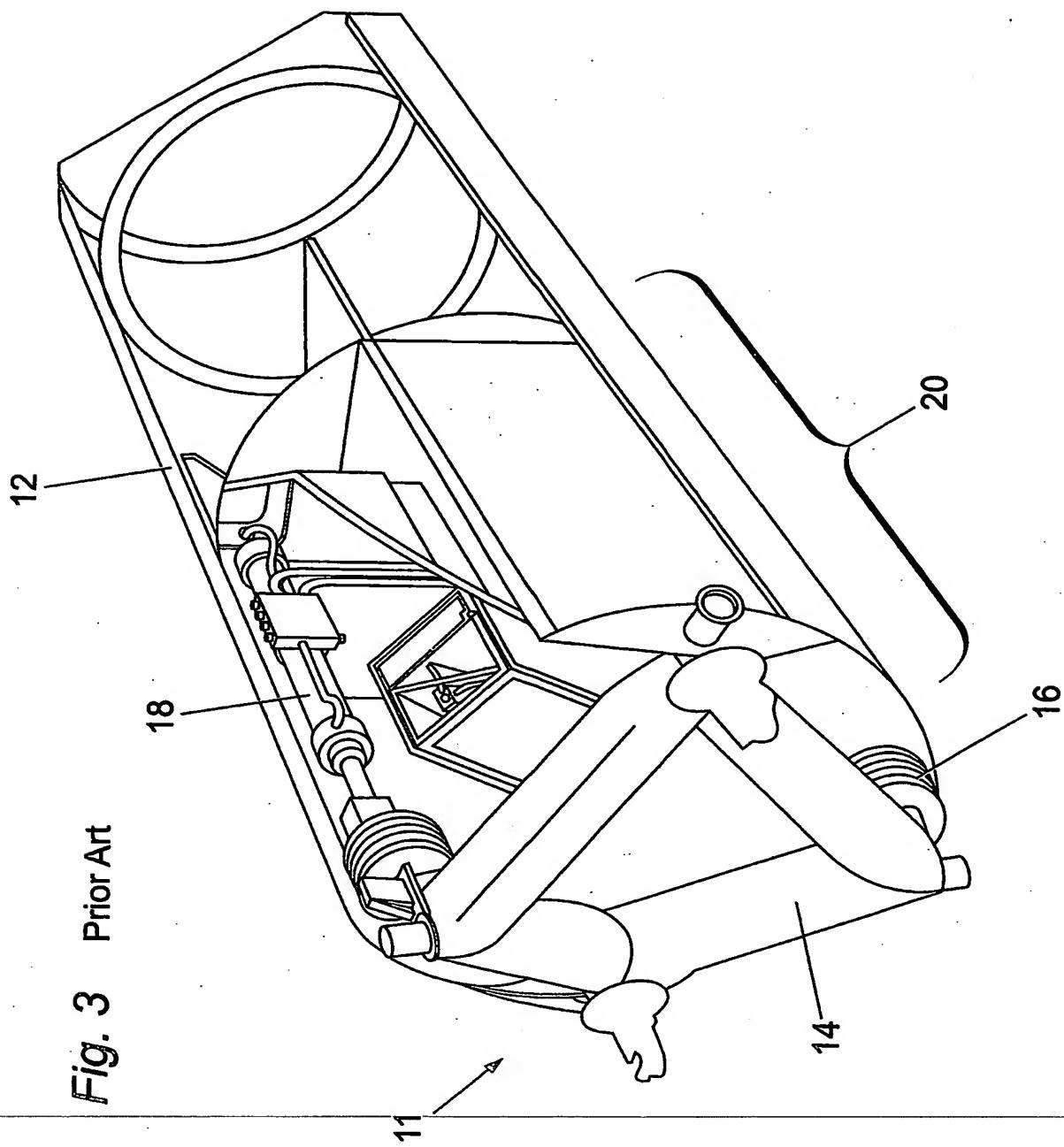


Fig. 3 Prior Art

4 / 12

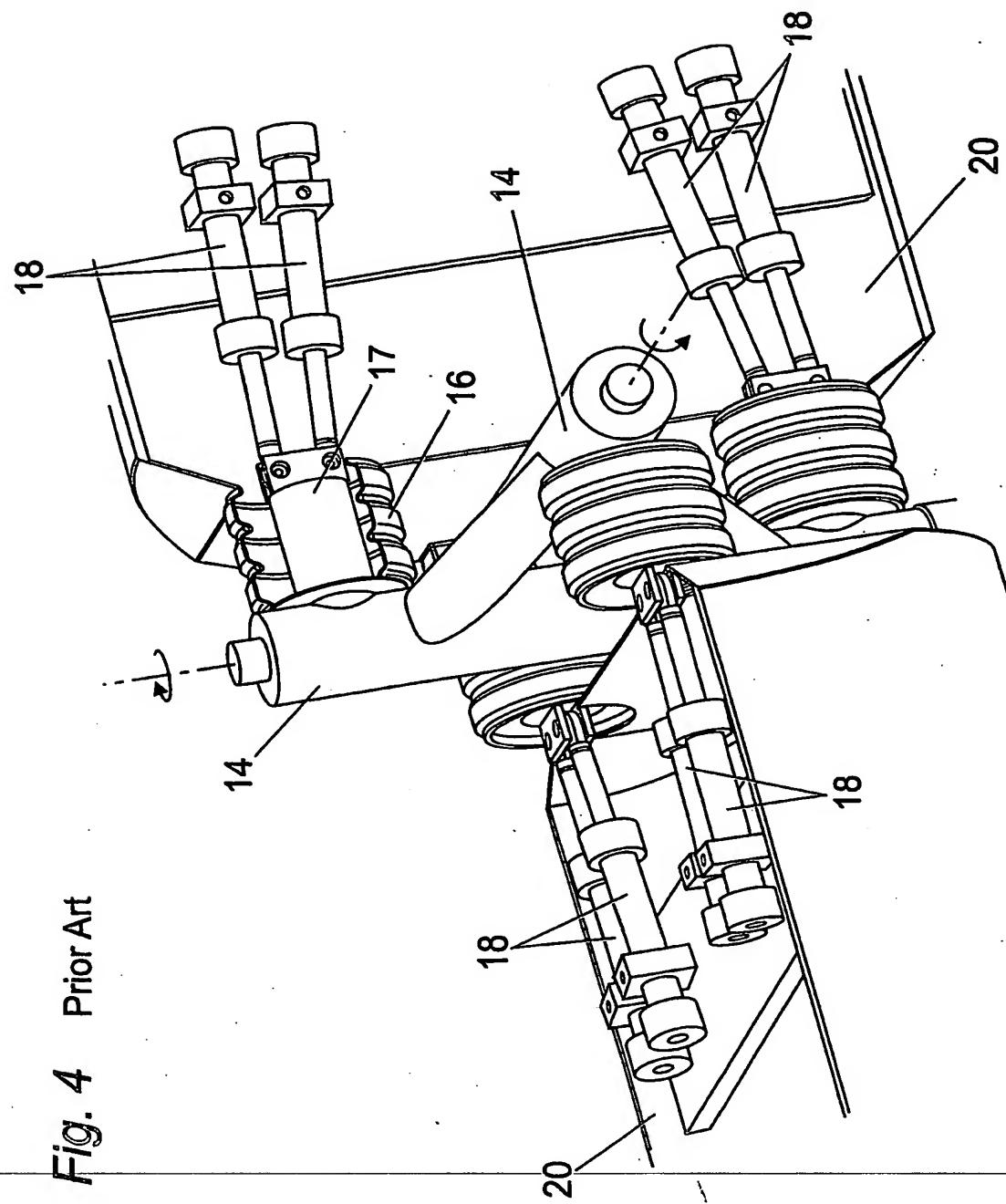


Fig. 4 Prior Art

5 / 12

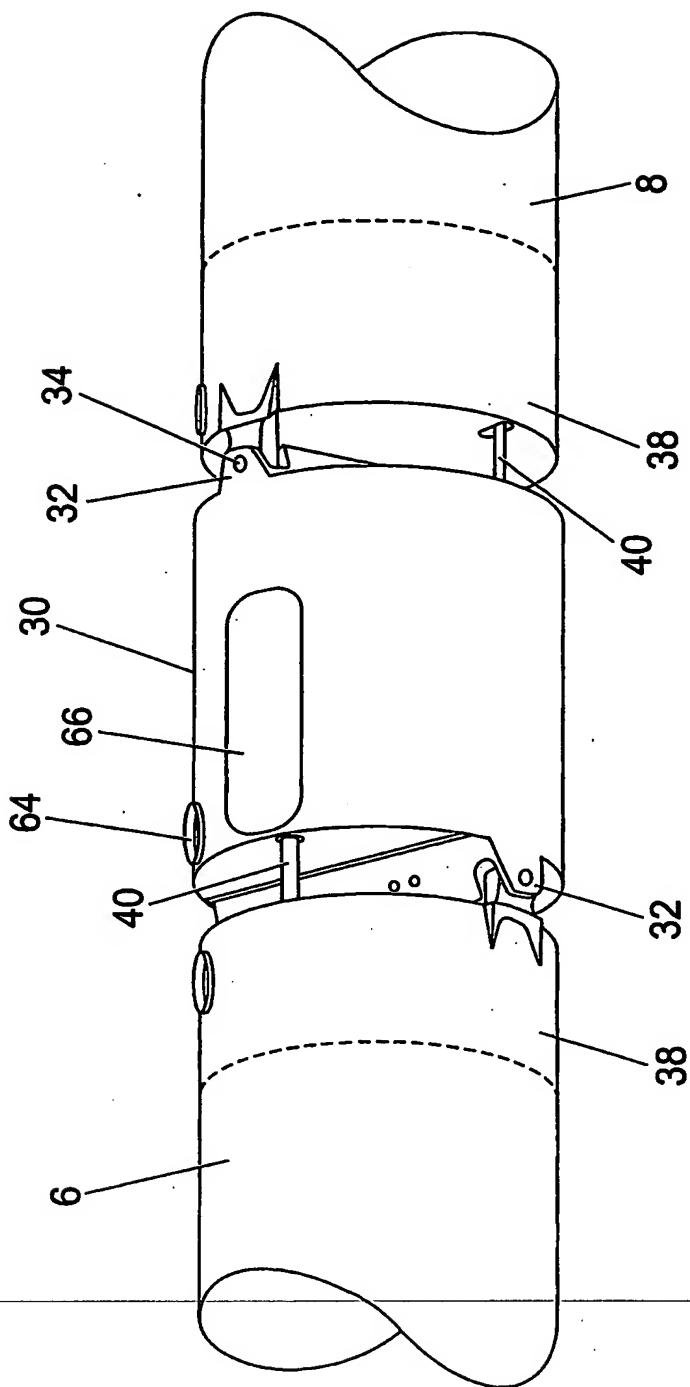


Fig. 6

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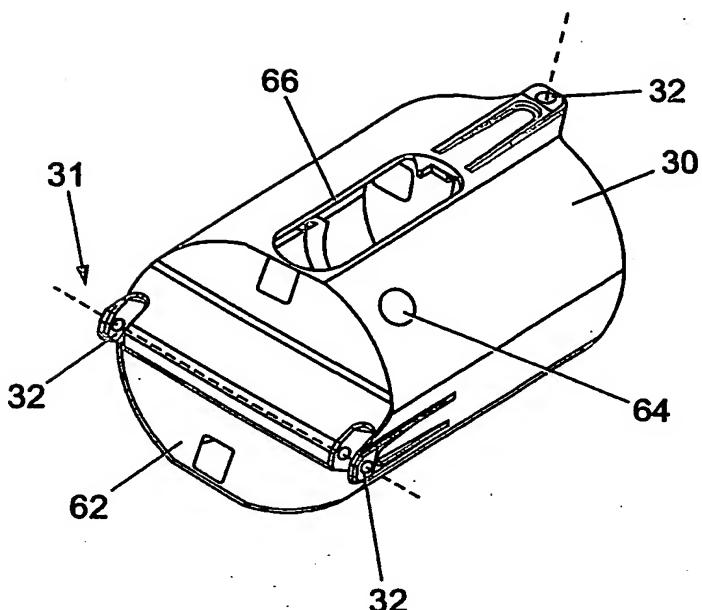


Fig. 7

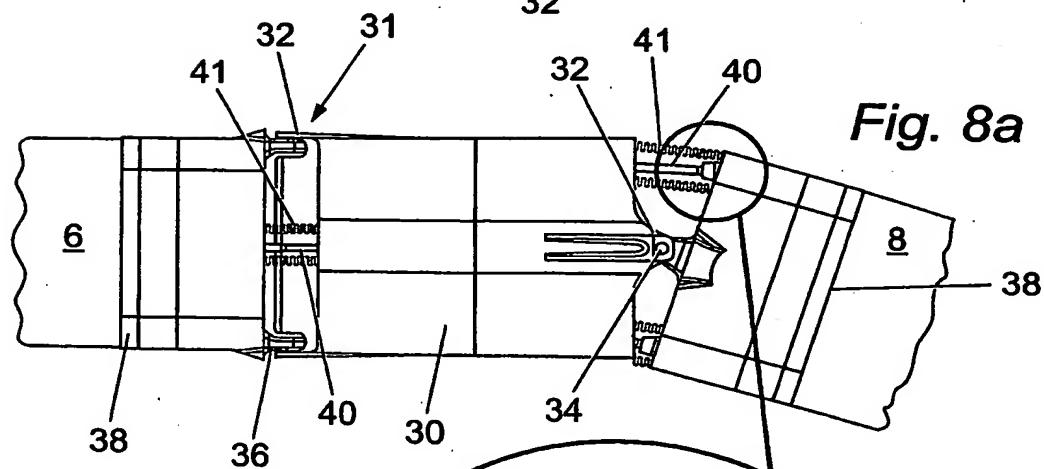


Fig. 8a

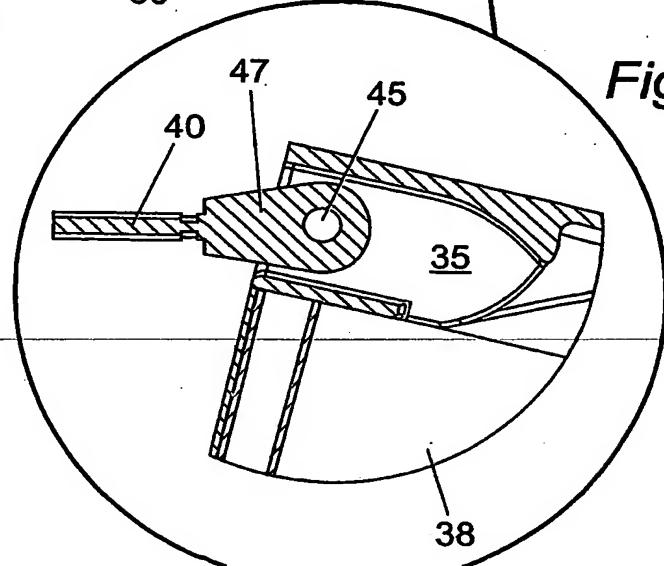


Fig. 8b

7/12

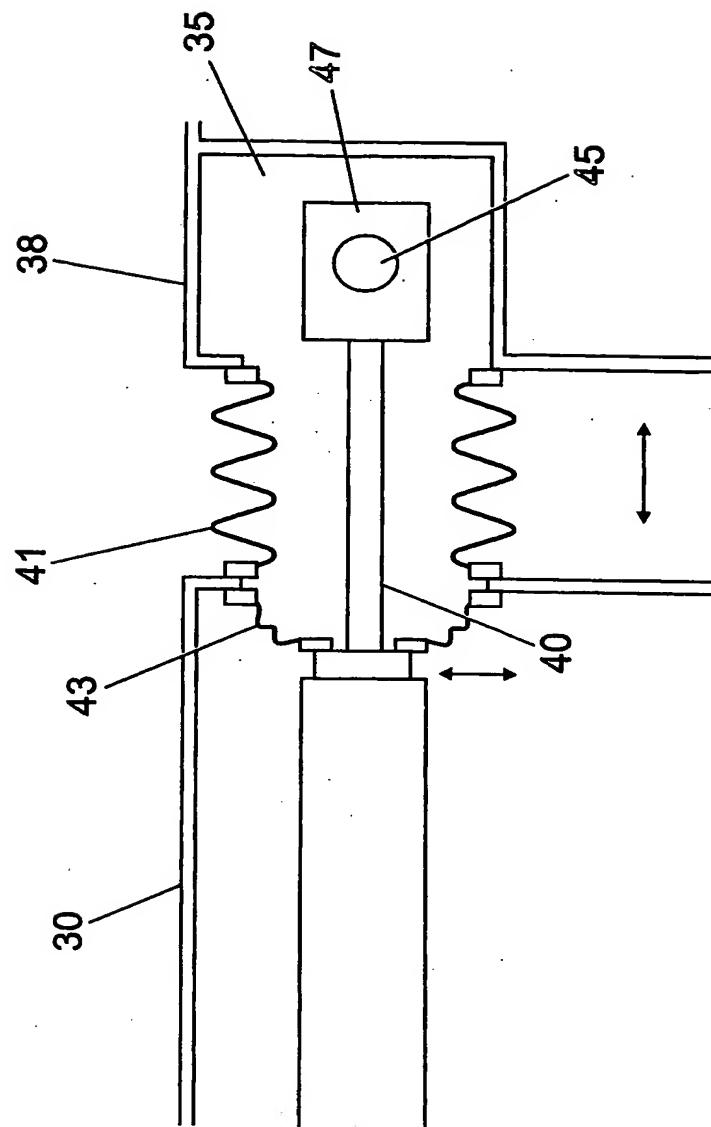


Fig. 8c

8 / 12

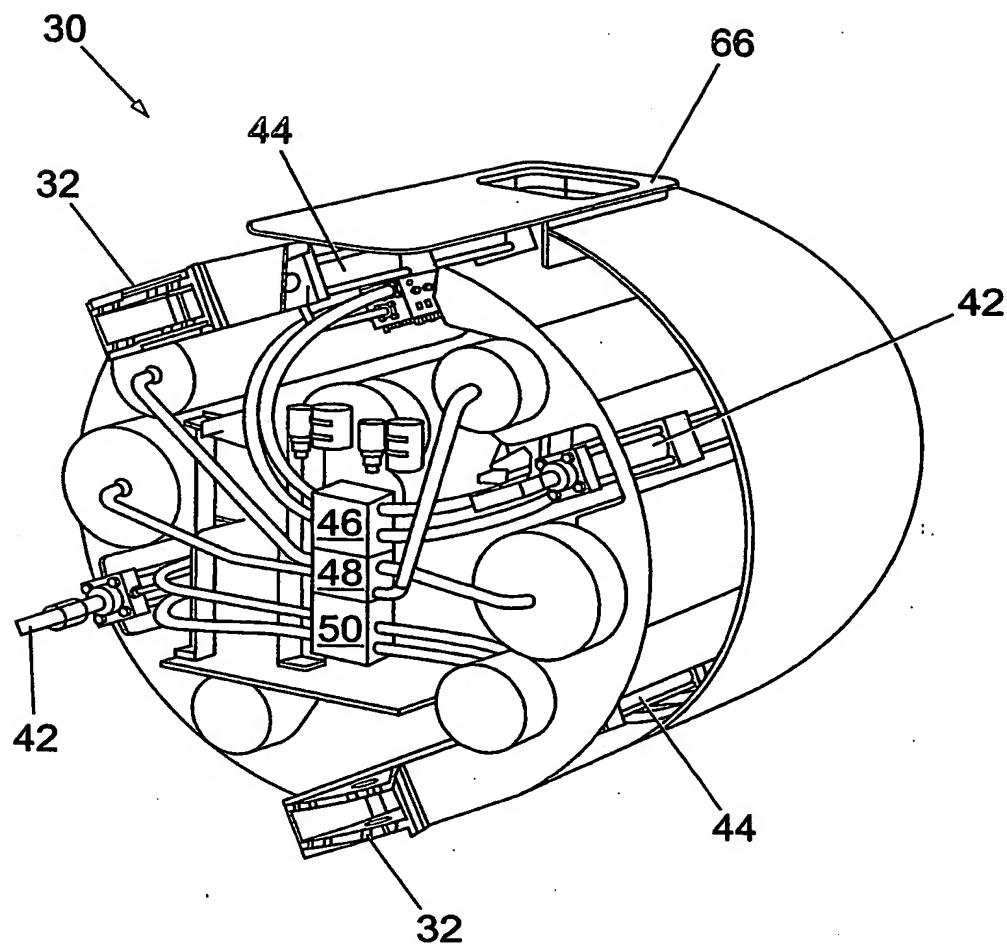


Fig. 9

9 / 12

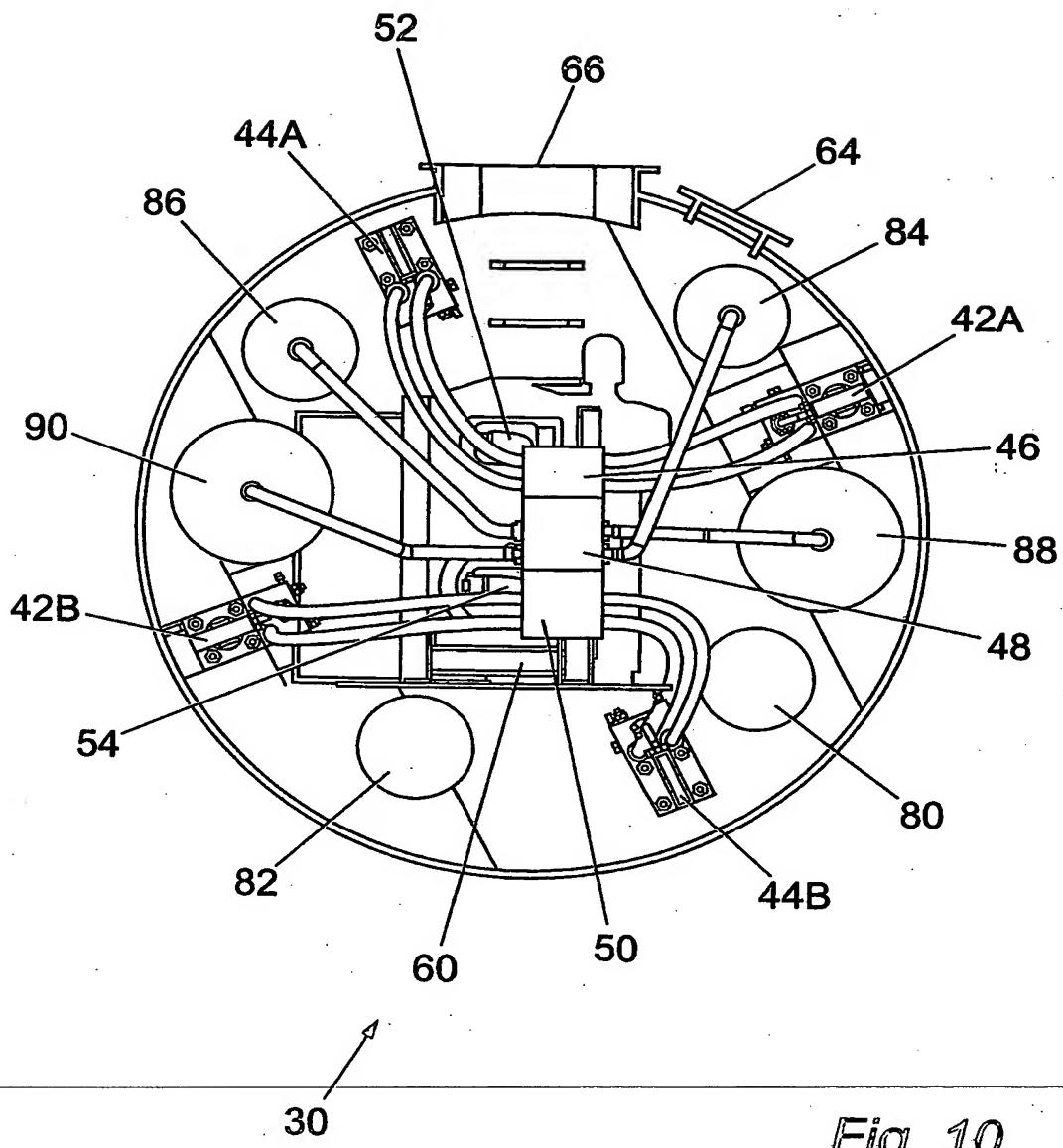


Fig. 10

10 / 12

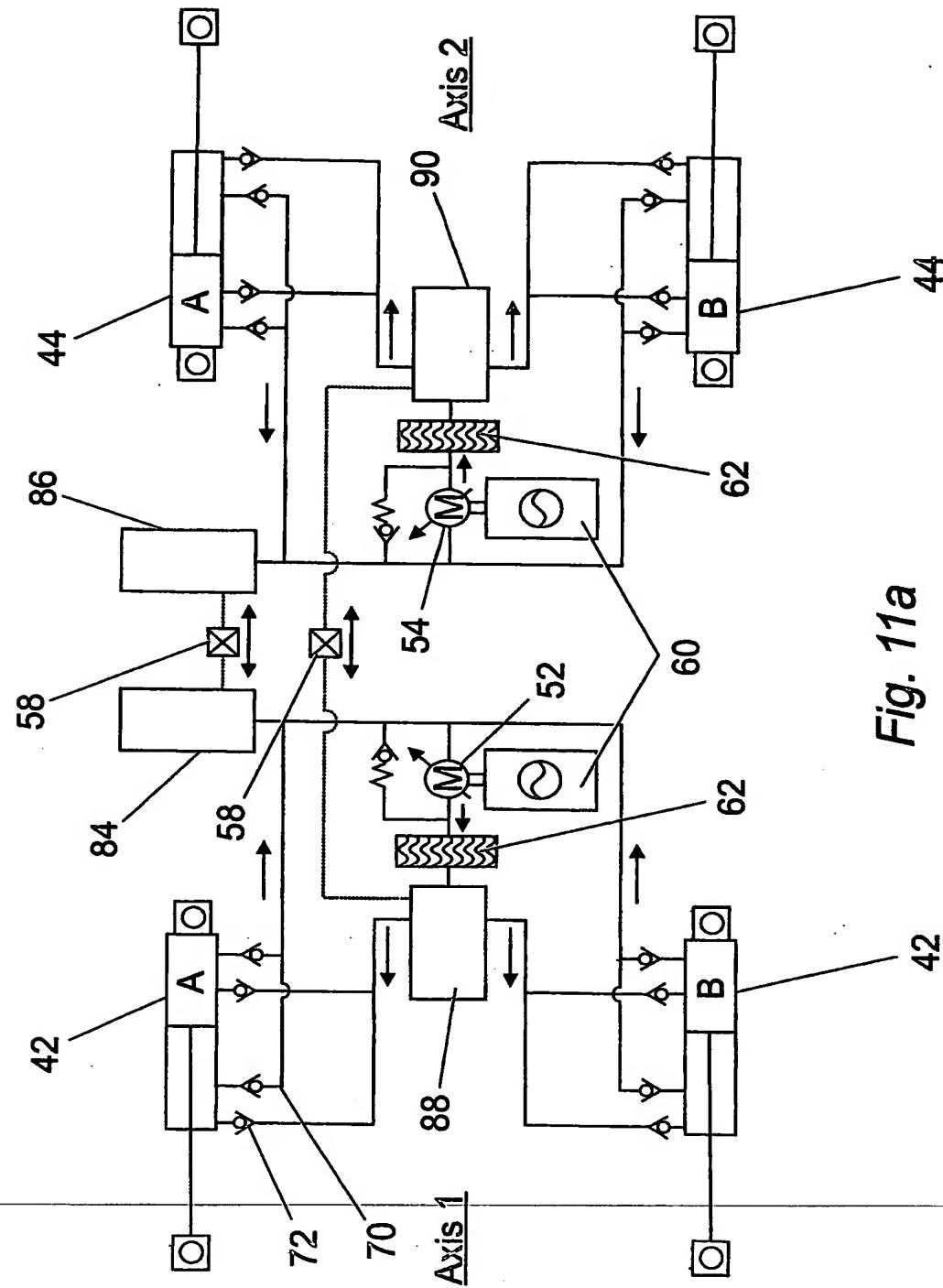


Fig. 11a

11 / 12

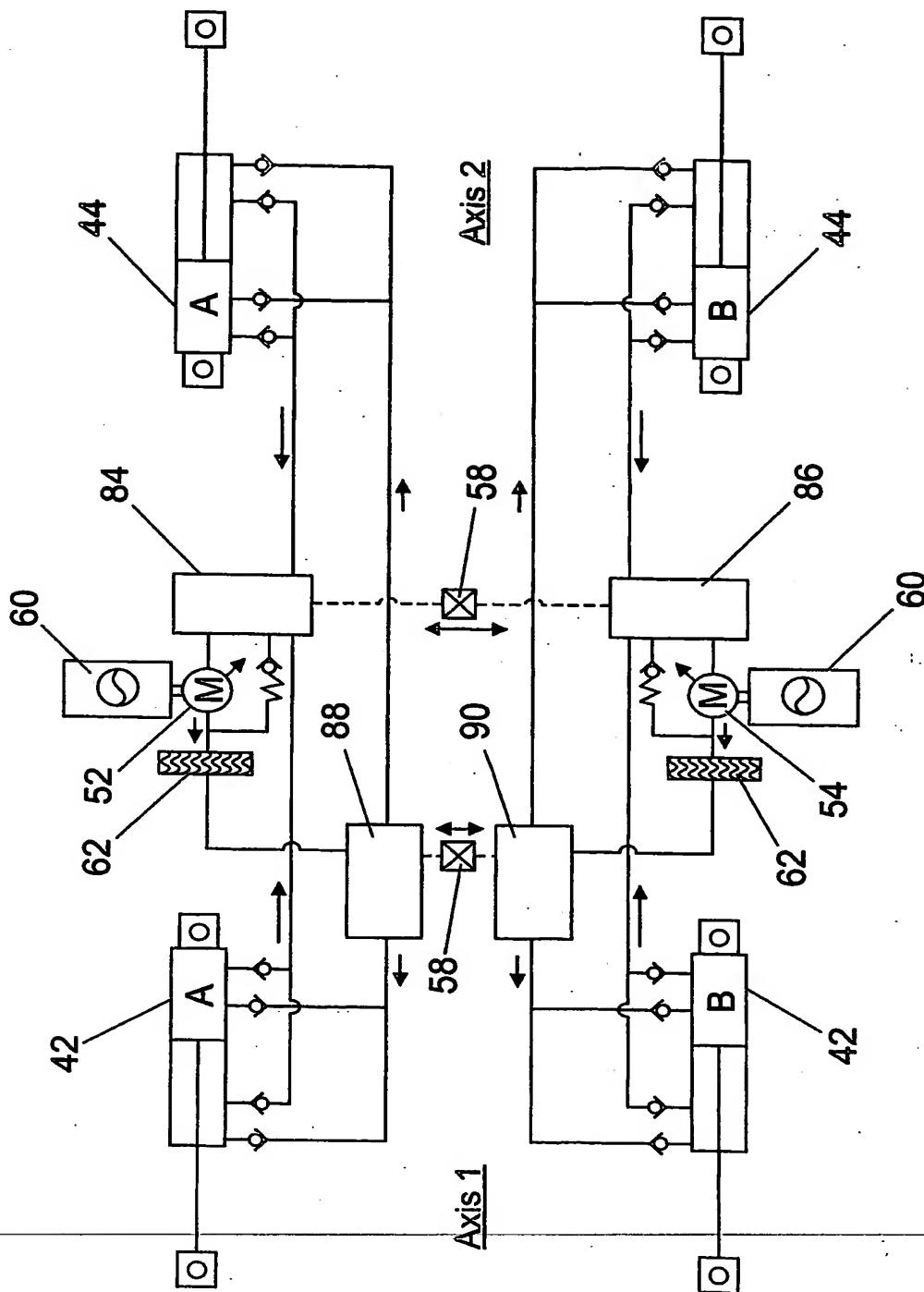


Fig. 11b

12 / 12

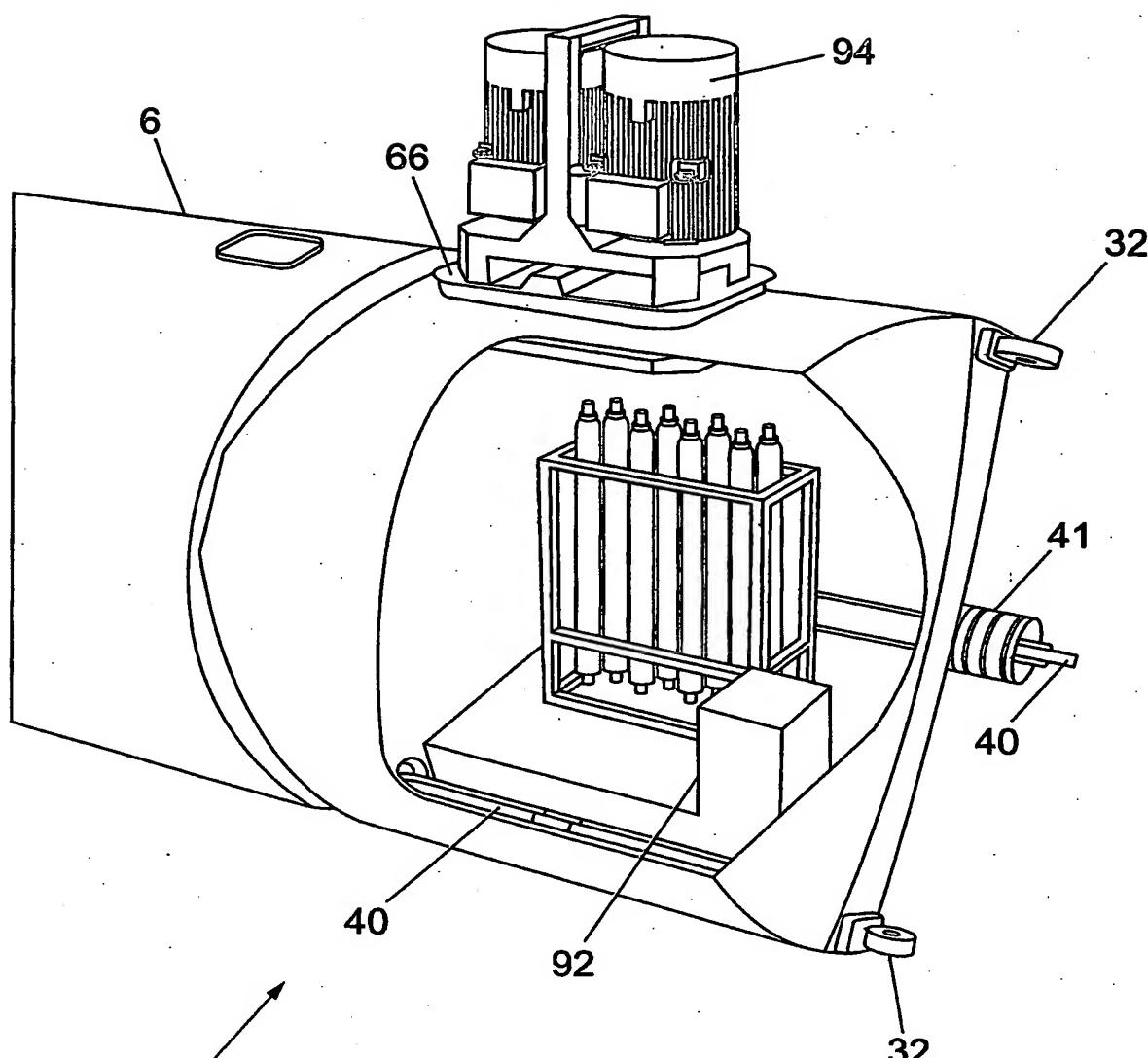


Fig. 12

INTERNATIONAL SEARCH REPORT

International Application No
PCT/GB2004/001443A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 F03B13/20

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC 7 F03B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 4 118 932 A (SIVILL ALISTAIR DAVID) 10 October 1978 (1978-10-10) column 1, line 62 – column 3, line 20; claims; figures 1-4	1-5, 7, 8, 12, 13, 20, 22, 23, 26, 27, 33, 34
X	US 4 077 213 A (HAGEN GLENN E) 7 March 1978 (1978-03-07)	1-4, 13, 18, 20, 27, 33, 34
Y	column 5, line 31 – column 6, line 22; figures 3-6, 9 column 6, line 63 – column 8, line 29	7, 8, 22, 23
		-/-

 Further documents are listed in the continuation of box C. Patent family members are listed in annex.

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Date of the actual completion of the International search

Date of mailing of the International search report

10 August 2004

25/08/2004

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Authorized officer

de Rool, M

INTERNATIONAL SEARCH REPORT

International Application No
PCT/GB2004/001443

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT		
Category	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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A		6,9,10, 14-16, 21,24, 25,28-30
X	GB 2 036 190 A (ENERGY SECRETARY OF STATE FOR) 25 June 1980 (1980-06-25) the whole document	1,2,4,5, 13,20, 27,33,34
X	US 1 018 678 A (F.M. NELSON) 27 February 1912 (1912-02-27) the whole document	1,2,4, 13,18, 20,27, 33,34
X	US 1 078 323 A (L.A. TRULL) 11 November 1913 (1913-11-11) the whole document	1,2,4, 18,20,33

INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No

PCT/GB2004/001443

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